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**14. ABSTRACT**
This study incorporated virtual height traces measured by ionosondes directly into an objective analysis (OA) algorithm. The OA algorithms ingest available data sets to construct coherent maps that represent the larger scale behavior of the ionosphere. A forward model which calculates the virtual height profile form a given electron density distribution was developed and incorporated into the Ionospheric Data Assimilation Three Dimensional (IDA3D) OA algorithm. In addition, IDA3D was modified to ingest nonlinear observations. Initial tests of the modified IDA3D indicate a good fit between the IDA3D predictions of the virtual height to the observed virtual heights. The IDA3D electron density profiles agree well with the electron densities calculated by a state-of-the-art digisonde inversion algorithm. In addition, the valley region between the E and F layers is generated in IDA3D by incorporating the virtual height traces.

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# FINAL PERFORMANCE REPORT

**Period of Performance: 1 May 2005 – 31 January 2006**

**GRANT FA9550-05-1-0316**

# INCORPORATING DIGISONDE TRACES INTO THE IONOSPHERIC DATA ASSIMILATION THREE DIMENSIONAL (IDA3D) ALGORITHM

**BY**

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## OBJECTIVE

Applied Research Laboratories, The University of Texas at Austin (ARL:UT), proposes to incorporate digisonde data into a global ionospheric analysis algorithm to provide more accurate, global specifications of the ionospheric space weather. This work will improve the Ionospheric Data Assimilation Three Dimensional (IDA3D) algorithm, which produces global electron density specifications. The IDA3D will be modified to incorporate the return time spectrum (or virtual height profile) observed by digisondes distributed around the world. The improved specifications can be made available to the United States Air Force (USAF) operational planners, allowing them to respond appropriately to the ionospheric weather.

## WORK PREFORMED

The tasks preformed under this grant falls into three major categories: development of the forward model $H$, modification of IDA3D to incorporate nonlinear observations, and validation of the new IDA3D results. In addition, it was necessary to become familiar with the digisonde observations and data availability. To become familiar with the digisonde data, two days of data from the Digital Ionogram DataBase (http://ulcar.uml.edu/DIDBase/), the largest digisonde database, were visually examined. These data were processed by the Automatic Real Time Ionogram Scaler with True Height (ARTIST) [*Reinisch and Huang,* 1983] program into electron density profiles, and the IDA3D algorithm constructed space weather maps for the 29-30 October 2003 magnetic storm with these profiles. The processing of the digisonde data for this storm study provided an extensive introduction into the data timeliness, quality control, and database issues involved in using digisonde data.

The first task was to develop a forward model to predict the virtual height from a given array of gridded electron densities. The forward model was developed from the theory developed in *Budden* [1961]. The virtual height $h'(f)$ at a given digisonde emission frequency $f$ is given by

$$h'(f) = \int_0^{z_r} \mu'(f, f_p(z))dz \tag{1}$$

where $\mu'$ is the real component of the group index of refraction, $f_p$ is the electron plasma frequency, and $z_r$ is the reflection height of the wave. The electron plasma frequency is related to the electron density by $f_p = c\sqrt{n}$ where $n$ is the electron density and $c$=8.97866275 Hz m$^{-1.5}$. The reflection height $z_r$ is given by $f_p(z_r) = f$. The real group index of refraction is given by

$$\mu'(f, f_b(\lambda,\phi,z), B(\lambda,\phi,z), \Theta(\lambda,\phi,z)) = \frac{(1-X-\mu^2)}{D\mu} + \frac{mY_L^2(1-X^2)(1-\mu^2)}{2D\mu\sqrt{\alpha}} + \frac{1}{\mu} \tag{2}$$

where $B$ is the strength of the magnetic field at a given geographic latitude $\lambda$, geographic longitude $\phi$, and altitude $z$, $\Theta$ is the angle between the magnetic field line and the propagation direction of the wave (assumed to be vertical), $X = (f_p/f)^2$ is the ratio of the plasma frequency to the emission frequency, $Y=g_pB/f$ is the ratio of the electron gyrofrequency to the emission frequency and $g_p$=2.799249247 x $10^{10}$ C/kg, the subscripts $L$ and $T$ denote the longitudinal (cos($\Theta$)) and transverse (sin($\Theta$)) components of the waves, $m$ is the mode factor with $m$=1 for the ordinary (O) mode of the wave and –1 for the extraordinary (X) mode, $\mu$ is the real phase index of refraction given by

$$\mu = \sqrt{1 - \frac{X(1-X)}{D}} \tag{3}$$

and D and $\alpha$ are simplifying algebraic functions given by

$$D = 1 - X - \tfrac{1}{2}Y_T^2 + m\sqrt{\alpha}$$

and

$$\alpha = \tfrac{1}{4}Y_T^4 + Y_L^2(1-X)^2 .$$

As $X$ approaches 1, $\mu'$ goes to infinity, and $\mu$ goes to 0. However, *Budden* [1961] published a reliable approximation to $\mu'$ for both the O-mode and the X-mode when is near the reflection altitude. The O-mode corresponds to reflection at $X$=1. The approximation that is valid for 1-$X$<<1 is

$$\mu'_{approx} \approx \frac{1}{\sin\Theta\sqrt{1-X}}\left(1 - \frac{3(1-X)}{2\tan^2\Theta}\right) \tag{4}$$

The X-mode corresponds to reflection at $X$=1±$Y$ with an approximation for 1±$Y$-$X$<<1 produces

$$\mu'_{approx} \approx \frac{2 \mp Y}{\sqrt{2(1 \mp Y - X)(1 \mp Y)(1+\cos^2\Theta)}} \tag{5}$$

where the negative sign corresponds to the $X=1-Y$ reflection and the plus sign corresponds to the $X=1+Y$ reflection. The forward model $H(n(\lambda,\phi,z))$ for a given electron density distribution is a numerical approximation to the integral. The electron densities specified on a grid of $L$ horizontal points (irregularly spaced in latitude and longitude) and $K$ vertical points with the densities placed in the center of the grid cell. The forward model is given as

$$H(n_{l,k}) = \sum \mu'(n_{in})dz + \int_{f_{approx}}^{1} \mu'_{approx}\frac{dz}{df_p}dz \tag{6}$$

The first term in the forward model is a loop through the grid over those frequencies less than the emission frequency. The electron density is linearly interpolated between the surrounding data points, and the vertical step distance $dz$ is step to 1.0 km/μ'. As the forward model steps in altitude, the approximation (4) is compared with the numerical solution (2). When the two values are within 5%, the integral is solved analytically. For the O-mode, the analytic term reduces to

$$\int_{f_{final}}^{1} \mu'_{approx} \frac{dz}{df_p} dz = \frac{dz}{df_p}\frac{f}{2\sin\Theta}\left[\left(1-\frac{3}{4\tan^2\Theta}\right)\arccos(1-2(1-X)) + \frac{3\sqrt{X(1-X)}}{2\tan^2\Theta}\right] \quad (7)$$

The altitude derivative is the inverse of the slope of the linear interpolation.

This forward model is dependent upon both a background electron density and a magnetic field model. An ideal 3DVAR algorithm does not utilize any inputs, which are not within the background model. However, the magnetic field within the ionosphere is only weakly dependent upon the plasma conditions. During magnetic storms, the changes in the low altitude magnetic field strength are less than a few percent. In addition, the magnetic field is a secondary term for the O-mode virtual heights. Hence, the magnetic field is considered to be static in time, and an independent magnetic field model does not violate the spirit or the functionality of 3DVAR. At present, the International Geomagnetic Reference Field (IGRF) model was used for the magnetic field. The forward model adequately calculates the virtual height distribution from a given electron density profile.

The second task was to implement the forward model into IDA3D. The fundamental

$$\underline{x}_a = \underline{x}_b + \mathbf{P_b H^T}[\mathbf{H P_b H^T} + \mathbf{P_o}]^{-1}(\underline{y}_o - H(\underline{x}_b)) \quad (8)$$

3DVAR equation, which IDA3D solves, is
where $\underline{x}_a$ is the analysis vector, $\underline{x}_b$ is the background model vector, $\mathbf{P_b}$ is the error covariance matrix associated with the background model, $\mathbf{P_o}$ is the error covariance matrix associated with the observations, $\mathbf{H}$ is the transformation matrix, $\underline{y}_o$ is the observation vector, and $H$ is the forward model. For a linear forward model, the transformation matrix is equal to the component parts of the forward model, $H(\underline{x}) = \mathbf{H}\underline{x}$. However, the transformation matrix is different for a nonlinear forward model. It is given by the derivative with respect to $\underline{x}$ at the background model. For the virtual heights, the elements of the transformation matrix are given by

$$H_{l,m} = \left.\frac{d\Delta h'_l}{dn_b}\right|_m = \sum \frac{d\mu'(f_p)}{df_p}\frac{\partial f_p}{\partial n_{b,m}} dz \quad (9a)$$

outside of the analytic regime

$$H_{l,m} = \frac{f}{2\sin\Theta}\frac{dz}{df_p}\left[\left(1-\frac{3}{4\tan^2\Theta}\right)\frac{2}{\sqrt{2(1-X)}} + \frac{3(1-2X)}{4\tan^2\Theta\sqrt{X(1-X)}}\right]\frac{\partial X}{\partial n_{b,m}} \quad (9b)$$

and inside of the analytic regime. The subscripts $l$ and $m$ correspond to the observation and grid elements, respectively. It should be noted that the second two terms in equation (9) have contributions to the grid cells above ($m$+1) and below ($m$-1) the reflection height.

In addition to developing the transformation matrix, the basic convergence loop of the algorithm was modified. Because the matrix inversion in equation 8 is numerically and computationally difficult and only the solution is important, equation 8 is solved by a steepest descent algorithm, which iterates to convergence. After the first iteration, the previous iteration's analysis vector is used as the background vector. For the nonlinear observations, the transformation matrix is updated at every iteration, and the combined matrix $\mathbf{HP_bH^T}+\mathbf{P_0}$ is recalculated. This increases the IDA3D runtime, but not prohibitively. This new convergence loop allows IDA3D to treat nonlinear data.

The last task was to conduct test of the new data source. The test period for this study was October 30, 2003. While an extreme storm period, it has been previously studied with IDA3D. The data is locally available and previously quality checked. In addition, IDA3D maps using ARTIST-calculated profiles from hand scaled ionograms are available for comparison. The first test run of the IDA3D used only O-mode autoscaled virtual height profiles from five different digisondes. The assumed error in the virtual height was 10%. The background model used was the Riley-ICED-Bent-Gallagher (RIBG) model. Figure 1 shows a comparison between the measured digisonde virtual heights and the IDA3D and RIBG calculated values for the Osan digisonde (URSI code SN437, 37.1° lat, 127.0° long), while Fig. 2 is a similar comparison between the IDA3D, RIBG, and ARTIST calculated electron density profiles. Figures 3 and 4 are similar plots for the Dyess digisonde (URSI code DS932, 32.4° lat., 260.0° long). A similar run was also conducted with the full set of available observations, including GPS slant total electron content (TEC) from ground and satellite-based receivers and *in situ* electron density measurements from orbiting spacecraft. As these figures show, IDA3D is able to reproduce the measured virtual height profiles well. The IDA3D electron density profiles produced by including the virtual heights are also in good agreement with the ARTIST profiles. One interesting feature of this study is the development of the valley region in the IDA3D analysis. These valleys tend to be thin layers.

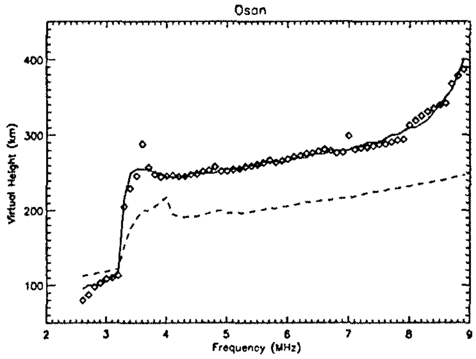


**Figure 1.** A comparison between the measured virtual height profile (solid line) with a virtual height profile calculated from the RIBG model (dashed line) and the IDA3D analysis (diamond symbols) for the Osan (URSI SN437) digisonde.

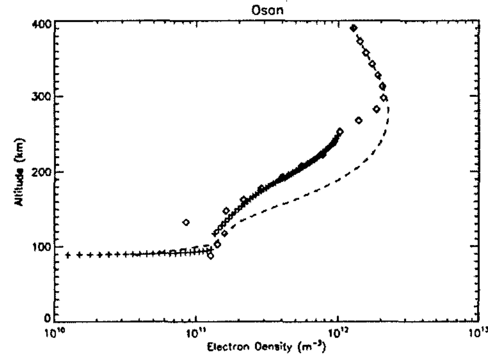


**Figure 2.** A comparison between ARTIST produced electron density profiles (+) with the RIBG model (dashed line) and the IDA3D analysis (diamond) for the Osan station.

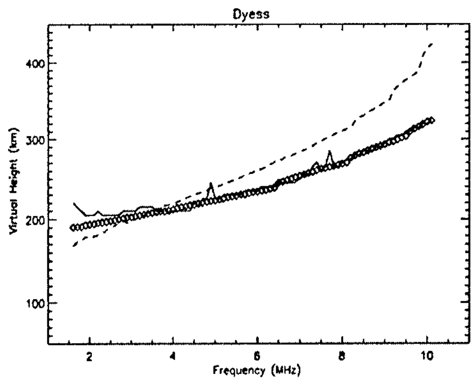


**Figure 3.** A virtual height comparison for the Dyess digisonde. The solid line shows the measured values, the dashed lines gives the profile calculated from RIBG, and the diamonds show the IDA3D virtual heights.

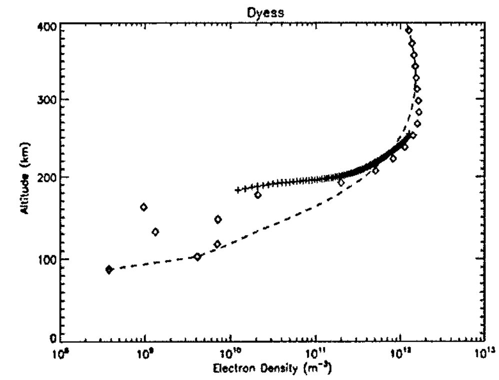


**Figure 4.** A comparison between ARTIST produced electron density profiles (+) with the RIBG model (dashed line) and the IDA3D analysis (diamond) for the Dyess station.

## REFERENCES

Budden, K. G., *Radio Waves in the Ionosphere,* University Press, Cambridge, 1961.

Reinisch, B. W. and X. Huang, Automatic calculation of electron density and profiles from digital ionograms, 1. Automatic O and X trace identification for topside ionograms, *Radio Sci.*, 17, 421, 1982.

## NEW FINDINGS

The measured virtual height traces can be directly ingested into a 3DVAR algorithm. In doing so, reasonable agreement is reached between the 3DVAR solution and the solution presented produced from the state-of-the-art inversion model. In addition, the analysis profile produces the valley region between the E and F layers.

## PERSONNEL SUPPORTED

Research Associate
Graduate Student
Undergraduate Student

**PUBLICATIONS**

Variations in the Midlatitude and Equatorial Ionosphere during the October 2003 Magnetic Storm, T. W. Garner, G. S Bust, T. L Gaussiran II and P. R. Straus, submitted to *Radio Science* September 30 ,2003, Presently working on the Reply to the Reviewers.

Incorporating Digisonde Traces into an Ionospheric Objective Analysis Algorithm, T. W. Garner, G. S. Bust, and S. Kilpatrick, Under preparation, to be submitted to *Space Weather.*

**INTERACTIONS**

Dr. Garner attended the Ionospheric Effects Symposium (IES) in May 2005, and was an invited speaker at the International Reference Ionosphere (IRI) Workshop in June 2005. In addition, Dr. Garner attended the International Radio Science Union (URSI) Meeting in January 2006. At the IES meeting, Dr. Garner was able to speak with Dr. Ivan Galkin from the University of Massachusetts-Lowell. Dr. Galkin manages the Digital Ionogram Database (DIDBase), which is the main database for digisonde data. These discussions concerned the needs for automated processing of the digisonde data. At the IRI workshop, Dr. Garner was able to discuss some of the outstanding difficulties in ionosonde processing with Dr. Bodo Reinsch who has developed the popular digisonde. At the URSI meeting, Dr. Garner was able to present the initial results of this study and to get feedback from the larger digisonde community. He has been asked to participate in an international digisonde data format discussion group led by Dr. Terry Bullet.

Incorporating Virtual Height Profiles into the Ionosphere Data Assimilation Three Dimensional (IDA3D) Algorithm, T W Garner, G S Bust, and S Kilpatrick, presented at the International Union of Radio Science (URSI) winter meeting, Boulder, Colorado, January 2006.

**NEW DISCOVERIES:** None

**HONORS/AWARDS:** None

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